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Sensitivity of spatial integration to perceptual cues is preserved in healthy aging

Bat-Sheva Hadad *

Department of Psychology, Emek Yezreel College, Emek Yezreel, Israel

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ABSTRACT

Spatial integration has been shown to substantially decline with age. We examined the mechanism underlying this age-related impairment. Young and older adults were tested on the ability to integrate contour elements across variations in the collinearity of the target elements, their spatial proximity, and the relative spacing of the target elements to the background noise elements (Δ). The results show that although contour integration generally declines with age, tolerating less noise (higher Δ) than in young adulthood, its mechanism is preserved over the years, critically depending on the relations between collinearity and spatial proximity of the contour elements. The results suggest that while spatial integration in childhood is limited by the absolute contour spacing, lacking the ability to use collinearity in order to overcome poor proximity among the elements, no changes occur in the sensitivity of contour integration to these perceptual cues at the other end of the lifespan. This suggests that the sensitivity of spatial integration to the statistics of natural scenes is preserved in aging.

1. Introduction

Aging is often associated with altered visual cognition. Although some functions, such as blur adaptation (Elliott et al., 2007), temporal integration (Andersen & Ni, 2008), shape perception (Norman et al., 2006; Wang, 2001), and visual short-term memory (e.g., Bennett et al., 2001; McIntosh et al., 1999; Sara & Faubert, 2000) show virtually no deterioration with age, other functions show considerable age-related decline. Considerable deterioration has been observed in optic flow (Atchley & Andersen, 1998), motion perception (e.g., Bennett, Sekuler, & Sekuler, 2007), stereopsis (Wright & Wormald, 1992), spatial or chromatic contrast sensitivity (Elliott, Sanderson, & Conkey, 1990; Elliott, Whitaker, & Macveigh, 1990), and face perception (e.g., Gao et al., 2009). These aging effects on vision are thought to reflect damage to the visual cortex, rather than being merely the result of age-related changes in the optical quality of the aging retina (e.g., Elliott et al., 2009).

A veridical interpretation of ordinary visual scenes depends crucially on spatial integration of visual information. This fundamental visual skill, however, has been found to extensively deteriorate with age (e.g., Andersen & Ni, 2008; Roudaia, Bennett, & Sekuler, 2008). Andersen and Ni (2008) found that spatial, but not temporal, integration was impaired in older age using a task requiring subjects to extract the shape of an object from moving dots. Del Viva and Agostini (2007) measured the threshold number of noise elements required to correctly detect a closed contour and found that fewer noise elements were required to impair sensitivity for older than for younger adults. Interestingly, the magnitude of impairment did not vary with contour inter-element proximities. Roudaia and colleagues showed that older observers required longer stimulus durations (Roudaia et al., 2011) and higher contrast in detecting C shapes contours, and that unlike younger observers, their performance was not facilitated by tangentially aligned stimulus in comparison to radial orientation (orthogonal to the C contour; Roudaia, Bennett, & Sekuler, 2008). McKendrick, Weymouth, and Battista (2010) recently showed that older adults require more elements than younger adults to discriminate closed contour shapes (McKendrick, Weymouth, & Battista, 2010). Altogether, these studies imply impaired spatial integration in the elderly. However, in most of these studies, impaired performance could reflect an overall reduction in the efficiently with which the aging visual system segregates contours from their cluttered background, rather than limitation in integration skills. The purpose of the present study was to reveal the mechanism underlying the weakened spatial integration in aging.

In young adulthood, spatial integration depends critically on collinearity among the elements (e.g., Field, Hayes, & Hess, 1993). The absolute spatial proximity among the contour elements is less important (Hess & Beaudot, unpublished data in Hess, Hayes, & Field, 2003; Kovács et al., 1999); instead, integration depends on the relative spacing of elements in the contour compared to the background (defined as delta (Δ)). Moreover, when the elements are highly co-linear, even weak effects of spatial proximity diminish (Hadad & Kimchi, 2008). These interactive effects of collinearity and proximity can be related to average statistical properties of natural contours (Geisler, Perry, & Ing, 2008; Hadad & Kimchi, 2008):

* Fax: +972 8 6428348.
E-mail address: bhadad@univ.haifa.ac.il

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collinear elements, which are likely to reflect parts of a real object, are efficiently integrated into a global shape, regardless of the spatial proximity among them. Non-collinear elements, on the other hand, which are less likely to reflect parts of the same object, are integrated into a shape only when they are spatially close to each other. We have recently shown that this sensitivity to the statistics of natural scenes is slow to develop. Unlike adults, integration in children was limited by spatial proximity regardless of collinearity and one strong cue did not compensate for the other. Only after age 14 did collinearity, the most reliable cue, come to compensate efficiently for spatial proximity (Hadad, Maurer, & Lewis, 2010).

Here, we examined the mechanism underlying the impaired spatial integration in the elderly, specifically, whether deterioration reflects age-related changes in integration skills and/or an overall reduction in the efficiently with which the aging visual system segregates contours from their cluttered background. We tested young and older adults on the ability to integrate contour elements as a function of spatial proximity and collinearity when relative spacing of elements in the contour compared to the background (Δ) was controlled. This allowed us to attribute any significant differences in delta thresholds between different degrees of proximity to limitations in the spatial range of contour integration rather than simply the effect of signal to noise ratio. If impaired grouping processes underlie the reduced spatial integration in the elderly, integration would show lower sensitivity to the perceptual cues of proximity and collinearity and to their interactive effects. If, however, reduced spatial integration in the elderly is due to a general reduction in the ability to segregate a signal from noise, integration would generally tolerate less noise but would show sensitivity to perceptual cues of proximity and collinearity and to their interactive effects, as demonstrated in young adults (Hadad, Maurer, & Lewis, 2010).

To study the mechanism of change in spatial integration through the lifespan we also compared this late-life performance to early-life performance recently obtained in children employing the same task (Hadad, Maurer, & Lewis, 2010). The comparison suggests aging is not necessarily development in reverse.

2. Method

2.1. Participants

Twelve younger (M = 22.75 years; range = 18–28 years; 7 females), and twelve older (M = 69.5 years; range = 65–80 years; 7 females) adults participated in the experiment. All met our criteria on a visual screening examination. Specifically, participants had a linear letter acuity (Lighthouse Visual Acuity Chart) of at least 20/25 in each eye with a maximum of −2 diopters of optical correction (to rule out myopia greater than 2 diopters which would reduce vision at our testing distance of 50 cm), worse acuity with a +3 diopter add (to rule out hypermetropia greater than 3 diopters), fusion at near on the Worth four dot test, and stereo acuity of at least 40 arcsec on the Titmus test. An additional three older participants were excluded from the final sample for not passing visual screening. A general health questionnaire was administered prior to testing, and none of the subjects reported having any visual disorders or major health problems. Older subjects also completed the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975) and all scores were within the normal range.

2.2. Apparatus and stimuli

Stimuli were generated on an Apple Macintosh G5 computer using the MATLAB programming environment (version 7.4.0.287. The MathWorks, Inc., Natick, MA, USA) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The stimuli were presented on a 21″ color CRT monitor (Dell P1130). Pixel resolution was 1600 × 1200, with one pixel corresponding to 0.021° at the testing distance of 50 cm, and the refresh rate was 85 Hz. Mean luminance was 60 cd/m^2. Participants viewed the displays binocularly.

We used a closed figure made up of 14 Gabor patches (Gaussian windowed sinusoidal gratings) arranged in a global pattern of an egg-like shape (see Fig. 1). The Gabor patches were positioned on the imaginary elliptical contour with a random starting point. The position of the contour was jittered up to 2° around the center of the screen so that its elements appeared in different spots but at roughly the same radius so as to minimize positional uncertainty (e.g., Hess & Dakin, 1999). Gabor elements were created by multiplying a sine wave grating with a spatial frequency of 3 cpd by a circular Gaussian envelope with standard deviation (σ) of 0.25°. Contrast within the elements was 88%.

The contour was embedded in a field of noise Gabor patches with random orientations that were distributed randomly across the visual field. The screen was divided into imaginary circles of increasing radii, with the number of circles varying with the spacing between the background elements, which was specified by a staircase procedure (i.e., averaged spacing among the background elements decreased over trials by adding circles of background elements). Noise Gabors were assigned randomly to the imaginary radii and the center of each was positioned randomly within ±5 pixels along the imaginary radius. A new random noise background was generated on each trial. All Gabor patches, both background noise and contour elements, were identical physically except for their locations and orientations.

There were two levels of collinearity of the target contour elements crossed with two levels of spatial proximity. Collinearity was manipulated by jittering the local orientation of the contour elements. This jittering is described by the angle α (Field, Hayes, & Hess, 1993). Specifically, for each proximity level we used α of 0° and 20°. For α = 0°, the orientations of the contour elements were parallel to the imaginary egg-shaped contour (i.e., high collinearity). For α = 20°, the orientations of the contour elements differed randomly either clockwise or anti-clockwise by 20° from the imaginary contour (i.e., low collinearity). The global curvature of the imaginary egg-shaped contour was kept constant across these different collinearity conditions. Therefore, varying the local orientation of each of the Gabors in the two collinearity conditions did not alter the angularity of the ends of the egg-like shape.

Spatial proximity was manipulated by varying the distance among the target contour elements while keeping constant the total number of elements in the background noise display as well as the total number of elements in the target contour. Consequently, changes in spatial proximity co-occurred with changes in the size of the target contour but without changes in the number of elements. Variations in spatial proximity are necessarily confounded with either changes in the size of the target or in the number of target elements. Previous studies showed that these two ways of varying spatial proximity produced the same results in adults (Hess & Beaudot, unpublished data, in Hess, Hayes, & Field, 2003). The distance between the elements in the target contour was set at 1.64° and 1.92° (when viewed from the testing distance of 50 cm) and resulted in a radius of the target ellipse of 5.71° and 6.84°, respectively. These values of proximity were chosen based on previous study in which they were shown to affect integration regardless of collinearity in early childhood, and when collinearity was low in young adulthood (Hadad, Maurer, & Lewis, 2010).

2.3. Procedure

The experimental protocol was approved by local research ethics board. The procedures were explained and informed consent

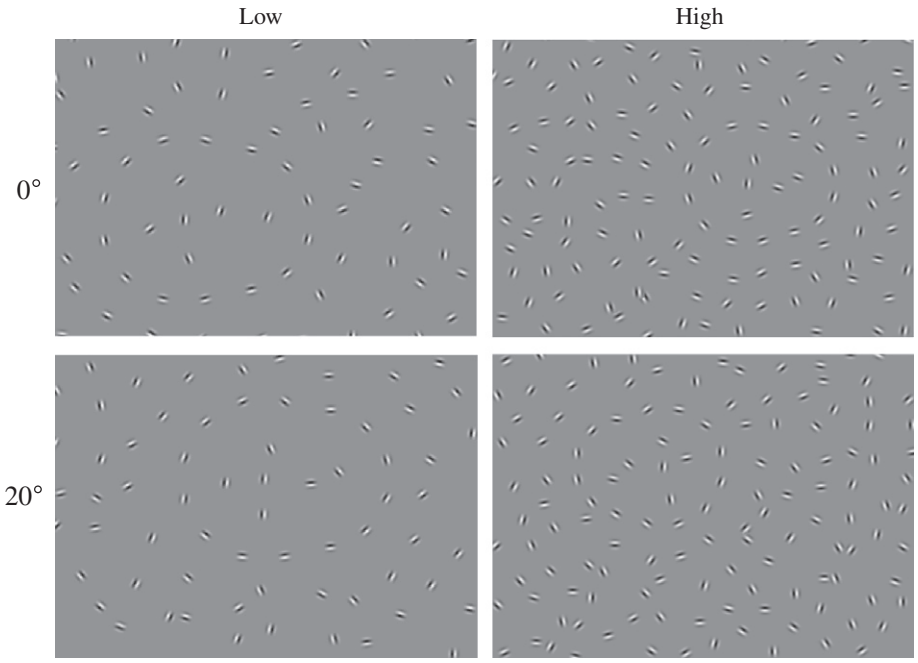

Fig. 1. The four conditions used in the experiment. For each of these four combinations of proximity (1.64° and 1.92°) and collinearity (α of 0° and 20°), a staircase procedure was used in which the average spacing between the background elements was reduced over trials. The first display with $\Delta = 1$ is shown for each of these combinations, where Δ represents the relative spacing of elements in the contour compared to the background.

Table 1
Mean thresholds expressed as the mean spacing (in pixels) of the background elements at threshold as a function of collinearity and proximity, for younger and older adults.

	Young adults		Older adults	
Proximity (°)	**±0**	**±20**	**±0**	**±20**
Low	41.46	50.64	44.02	57.35
High	34.70	40.44	36.34	47.11

was obtained. Observers completed four tests (combinations of collinearity and proximity), each preceded by demonstration and criterion trials. They were then given a practice run consisted of one full staircase procedure with high collinearity ($\alpha = 0°$) and the level of proximity to be used in the two tests to follow. The order of the four conditions was determined by a Latin Square. Observers completed the whole set of tests in one session that lasted approximately 40 min.

Observers sat 50 cm from the monitor, fixating on a 2.17° black circle in the center of the screen at the beginning of each trial. The fixation circle was removed after a variable interval and after a 250 ms delay, observers were shown the test stimulus for 1000 ms. The task was to judge whether the "head" of the egg-like shape was pointing to the right or to the left side of the screen and the experimenter pressed a corresponding key. Observers received auditory feedback about their accuracy. Contours pointing to the left or to the right appeared with equal probability and in random order. Averaged spacing among the background elements was varied according to a 1-up, 3-down staircase procedure, producing correct response rate equivalent to 79.4% accuracy (Levitt, 1971). In the first display, spacing among the background elements were 1.64° and 1.92°, for high and low proximities, respectively (to produce Δ of 1 in each of these conditions). After three consecutive correct responses, the staircase reduced the spacing of the background elements by 0.1 octave. Step-size remained at this size until an error was made, at which point step-size was reduced to 0.05 octave intervals. Testing continued until ten changes in the direction of the staircase ("reversals") occurred, which typically required 5 min. Threshold for each condition, defined as the minimum spacing among the background elements that permitted accurate discrimination of the direction of the egg-shape, was based on the geometrical mean spacing of the final six reversals. The experimenter watched the observers to ensure that they maintained central fixation and provided reminders to do so.

3. Results

Table 1 shows the mean thresholds (minimum spacing among the background elements for which the target contour could be detected) for each collinearity and proximity level, for younger and older adults.

In order to examine the spatial range of contour integration (i.e., effect of spatial proximity) independently from the effect of background spacing, thresholds were converted to delta values (Δ) by dividing them by the contour spacing of the target. A mixed-design ANOVA on the delta values was carried out with collinearity ($\alpha = 0°$ and 20°) and proximity (1.64° and 1.92°,) as within-subject factors and age as between-subjects factor. Significant differences in delta thresholds reflect limitations in the spatial range of contour integration rather than simply the effect of signal to noise ratio (Kovács et al., 1999). The resulting Δ values (background to contour spacing ratio) are presented in Fig. 2. Preliminary analyses revealed no significant effect of sex or order of conditions, nor any interactions involving these factors. The results were thus collapsed across these two factors.

The ANOVA revealed a marginally significant increase in delta values with age, $F(1,22) = 3.42$, $p = .07$, $\eta_p^2 = .14$, indicating a somewhat weaker contour integration in the elderly. As expected, there was also a significant effect of collinearity on delta values, $F(1,22) = 98.98$, $p < .0001$, $\eta_p^2 = .82$, indicating lower tolerance for dense background elements as collinearity of the contour elements decreased. Interestingly, weak collinearity perturbs integration in the elderly more than that in young adulthood, $F(1,22) = 5.49$,

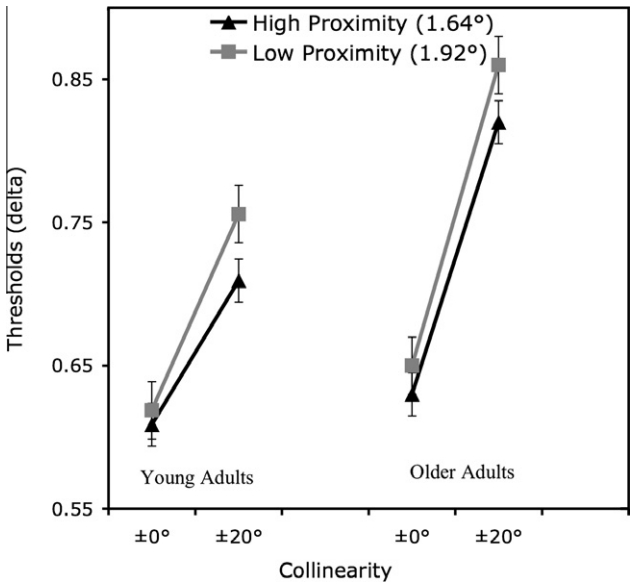

Fig. 2. Thresholds in Δ as a function of collinearity and proximity for younger and older observers. Δ represents the relative spacing of elements in the contour compared to the background (i.e., the values used in the analyses). Bars indicate within-subjects 95% confidence intervals.

$p < .03$, $\eta_p^2 = .20$, demonstrating a more substantial age related decline in integration under weak collinearity.

Most importantly, however, the analysis revealed a significant interaction between spatial proximity and collinearity, $F(1,22) = 15.82$, $p < .0001$, $\eta_p^2 = .42$. This interactive effect of collinearity and proximity on integration did not vary with age, $F(1,22) = 1.68$, $p > .21$, indicating that, for both young and older adults, no effect of spatial proximity on delta values was observed, $F(1,23) = 3.03$, $p > .10$, when contour elements were perfectly collinear ($\alpha = 0°$). However, when collinearity was low ($\alpha = 20°$), strength of integration varied strongly with proximity, $F(1,23) = 9.51$, $p < .005$, $\eta_p^2 = 0.29$, with high proximity leading to a stronger integration ($\Delta = 0.75$) than low proximity ($\Delta = 0.81$). Overall, these findings suggest that although spatial integration is somewhat weaker in the elderly, the interactive effects of the two cues – collinearity and spatial proximity – on integration did not vary with age.

4. Discussion

The results indicate that although contour integration generally declines with age, its mechanism is preserved over the years, depending critically on the relations between collinearity and spatial proximity of the contour elements. Specifically, in both young and older adults, contour integration is sensitive to the ratio of the spacing of background versus contour elements (Δ), rather than to the absolute spacing between the contour elements, when collinearity is strong (Hadad, Maurer, & Lewis, 2010; Kovács, 2000). However, when collinearity is relatively low, contour integration becomes more sensitive to the absolute spacing among the contour elements, with spatially close elements more easily integrated into a contour. Thus, like young adults, the older subjects seem to be able to use collinearity as a cue to compensate for poor proximity. This ability to use one strong cue to compensate for another seems symmetrical. As can be seen clearly in Fig. 2, when spatial proximity is high, the detrimental effect of low collinearity decreases. The interactive effects of collinearity and spatial proximity are consistent with the "association field" model (Field, Hayes, & Hess, 1993) in which the linking between orientation-tuned cells depends on their joint relative orientation and spatial position.

This relation between collinearly and spatial proximity in contour integration matches well the edge-alignment structure found in natural images (e.g., Geisler, Perry, & Ing, 2008). The probability that non-collinear segments compose the same object is relatively low, but it is much increased when these segments are spatially close. Collinear segments, however, are better candidates for integrating into a unified contour because they are more likely to reflect portions of a real object's contour, even when they have low proximity. This reflects the fact that natural contours are relatively smooth (Bex et al., 2001; Geisler et al., 2001; Ledgeway, Hess, & Geisler, 2005), even when there is a large spatial discontinuity between two parts of the contour caused, for example, by occlusion. An efficient computation of collinearity between elements that is less sensitive to spatial proximity (within a certain range) would therefore match the statistics of object contours in the real world. Both the younger and the older adults in the present study appeared to use such a mechanism. These results suggest that although aging may lead to an overall decline in the efficiency with which the visual system segregates signal from noise, it does not nullify the increased experience with the statistics of natural scenes accumulated over the years.

At first glance, the present finding suggesting the preservation of integration mechanism in the elderly seem inconsistent with earlier studies demonstrating aging effects on spatial integration (e.g., Roudaia et al., 2011). However, differences in levels of processing and difficulty of the task at hand (Bennett et al., 2001; Faubert, 2002; Habak & Faubert, 2000) may well explain the inconsistencies in age-related changes in visual function in general, and in spatial integration in particular. It has been argued that compensatory mechanisms may mask the effect of aging in relatively simple tasks but break down when task requirements are increased, resulting in a more pronounced effect of age in the more demanding tasks (Bennett et al., 2001). It seems therefore critical to disentangle the effects of demands of the task on age-related changes from deterioration in the specific visual function under investigation. The present study examined perceptual groupings underlying spatial integration in the elderly while controlling for task difficulty. We therefore used a staircase procedure to measure thresholds at accuracy level of about 79.4%, for each level of the grouping cues employed. Besides task difficulty, however, two different perceptual processes should be taken into account when examining spatial integration: grouping processes by which local elements have to be "assigned" to a particular contour, based on grouping cues such as collinearity and proximity, and segregation processes extracting the contour from its cluttered background. To uncover the mechanism underlying deteriorated spatial integration in the elderly we varied degrees of grouping cues of collinearity and proximity independently from signal-to-noise ratio by measuring thresholds in terms of delta (Δ; background to contour spacing ratio). We were thus able to show that no qualitative age-related changes occurs in integration abilities. In fact, integration in the elderly exhibits similar dependency on perceptual cues and sensitivity to statistics of real contours to that shown in young adulthood. The results reveal, instead, an overall reduction in the efficiency with which the visual system extracts a signal from noise, presumably reflecting the difficulty of the aging system to overcome higher levels of noise.

The neural mechanism underlying spatial integration in general and its deterioration in the elderly in particular, is yet unclear. However, decreased inhibition or elevations in spontaneous neural firing in older brains (e.g., Leventhal et al., 2003) may offer a possible explanation for the reduced efficiency in extracting a signal from noise observed here in the elderly. Schmolesky et al. (2000) found increased spontaneous activity, leading to lower signal-to-noise ratios, in early visual cortex of older, compared to younger macaques. This was attributed to changes in acetylcholine

regulation (Andersen & Ni, 2008) or reductions in GABA (Leventhal et al., 2003). Furthermore, application of GABA or GABA agonists has been shown to increase signal-to-noise ratios in macaque visual cortex (Leventhal et al., 2003). These reductions in inhibitory processes that have been linked to increased internal noise for related perceptual skills such as motion integration (Bennett, Sekuler, & Sekuler, 2007), may well account for the reduced ability to bear noise in the present task, leading to general reduced performance of older compared to younger adults. However, further investigation is clearly needed to uncover the neural mechanism underpinning perceptual grouping and segregation in the young and aging brain.

Examining the performance of children, young adults, and older adults, in the same task allowed us also to compare spatial integration across the lifespan. In our recent developmental study, age-related changes have been observed in the interactive effects of collinearity and spatial proximity on contour integration (Hadad, Maurer, & Lewis, 2010). While young adults are able to use one strong cue to compensate for the other, children are limited by the absolute contour spacing, lacking the ability to use collinearity in order to overcome poor proximity among the elements. In contrast, at the other end of the lifespan, no changes have been found in the sensitivity of contour integration to the interactive relations between collinearity and proximity. The different pattern of change characterizing spatial integration at the two ends of the lifespan is specifically associated with differences in the spatial range over which contour integration occurs (i.e., the effect of spatial proximity). Spatial integration during childhood is limited by the absolute spatial range contour integration independently from the effect of background spacing (Hadad, Maurer, & Lewis, 2010). In contrast, integration is only limited by the background to contour spacing ratio (Δ) throughout the adult life-course. It seems then that although the reduced ability to perceptually integrate individual elements into a shape is associated with both development and aging, the limitation in children is due to incomplete acquisition of statistics of contours whereas the limitation in old age is associated with reduced efficiency with which the visual system extracts a signal from noise. This pattern implies that at least for spatial integration, development and aging do not necessarily undergo the same mechanism of change.

Such asymmetries in perceptual change in development and aging support a recent model depicting a mechanism of cognitive change throughout the lifespan (Craik & Bialystok, 2006). By this model, *representations* – schemas for memory and knowledge, and *control* – fluid operations that enable intentional processing and adaptive cognitive performance, as well as their interactions, evolve across the lifespan and determine cognitive ability. Representational knowledge, defined as 'crystallized' intelligence, is thought to increase markedly during childhood, but remains relatively stable in old age. In contrast, cognitive control, defined as 'fluid' intelligence, increases in power, speed and complexity from infancy to young adulthood, and declines thereafter. Following the change in spatial integration through the lifespan, the present study demonstrates the increased accumulation of 'crystallized' knowledge (i.e., statistics of natural contours) during childhood, and its stable state in aging. At the same time, the findings demonstrate the enhancement of 'fluid' intelligence (i.e., segregating signal from noise) during childhood and its decline in aging.

Although research into visual functioning has largely been focused on how visual function is impaired as we grow older, equally important is the way the aging visual system supports the preservation or maintenance of certain aspects of visual functioning during the adult life-curse. Our data, suggesting the preservation of the ability to use perceptual cues in integrating individual elements into a global percept, is consistent with recent findings demonstrating the preservation of shape discrimination (Habak, Wilkinson, & Wilson, 2009) and the discrimination of sine wave gratings in a visual short-term memory task (McIntosh et al., 1999) in aging. These spared abilities highlight a potentially remarkable tendency of the aging nervous system to adapt itself to preserve certain functions (e.g., Owsley, 2011). Studying these few instances of stability of visual function during the adult life-course could reveal the mechanism of plasticity in the nervous system that mitigates the negative effects of aging-related structural and physiological changes in the brain.

In sum, the present study shows that aging may lead to a decline in the efficiency with which the visual system segregates signal from noise. Contrary to development, however, aging does not affect the sensitivity of integration to perceptual cues and therefore does not nullify the increased experience with the statistics of natural scenes accumulated over the years.

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References

Andersen, G. J., & Ni, R. (2008). Aging and visual processing: Declines in spatial not temporal integration. *Vision Research, 48*, 109–118.
Atchley, P., & Andersen, G. J. (1998). The effect of age, retinal eccentricity, and speed on the detection of optic flow components. *Psychology and Aging, 13*, 297–308.
Bennett, P. J., Sekuler, A. B., McIntosh, A. R., & Della-Maggiore, V. (2001). The effects of aging on visual memory: Evidence for functional reorganization of cortical networks. *Acta Psychologica (Amst), 107*, 249–273.
Bennett, P. J., Sekuler, R., & Sekuler, A. B. (2007). The effects of aging on motion detection and direction identification. *Vision Research, 47*, 799–809.
Bex, P. J., Simmers, A. J., & Dakin, S. C. (2001). Snakes and ladders: The contribution of temporal modulation to visual contour integration. *Vision Research, 41*, 3775–3782.
Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.
Craik, F. I. M., & Bialystok, E. (2006). Cognition through the lifespan cognition: Mechanisms of change. *Trends in Cognitive Sciences, 10*, 131–138.
Del Viva, M. M., & Agostini, R. (2007). Visual spatial integration in the elderly. *Investigative Ophthalmology & Visual Science, 48*, 2940–2946.
Elliott, S. L., Choi, S. S., Doble, N., Hardy, J. L., Evans, J. W., & Werner, J. S. (2009). Role of high order aberrations in senescent changes in spatial vision. *Journal of Vision, 9*, 1–16.
Elliott, S. L., Hardy, J. L., Webster, M. A., & Werner, J. S. (2007). Aging and blur adaptation. *Journal of Vision, 7*, 1–9.
Elliott, D. B., Sanderson, K., & Conkey, A. (1990). The reliability of the Pelli-Robson contrast sensitivity chart. *Ophthalmic & Physiological Optics, 10*, 21–24.
Elliott, D., Whitaker, D., & Macveigh, D. (1990). Neural contribution to spatiotemporal contrast sensitivity decline in healthy aging eyes. *Vision Research, 30*, 541–547.
Faubert, J. (2002). Visual perception and aging. *Canadian Journal of Experimental Psychology, 56*, 164–176.
Field, D. J., Hayes, A., & Hess, R. (1993). Contour integration by the human visual system: Evidence for a local 'Association Field'. *Vision Research, 33*, 173–193.
Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-Mental State": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research, 12*, 189–198.
Gao, L., Xu, J., Zhang, B., Zhao, L., Harel, A., & Bentin, S. (2009). Aging effects on early-stage face perception: An ERP study. *Psychophysiology, 46*, 970–985.
Geisler, W. S., Perry, J. S., & Ing, A. D. (2008). Natural systems analysis. In B. Rogowitz & T. Pappas (Eds.), *Human vision and electronic imaging. Proceedings SPIE* (Vol. 6806, 68060M).
Geisler, W. S., Perry, J. S., Super, B. J., & Gallogly, D. P. (2001). Edge co-occurrence in natural images predicts contour grouping performance. *Vision Research, 41*, 711–724.
Habak, C., & Faubert, J. (2000). Larger effect of aging on the perception of higher order stimuli. *Vision Research, 40*, 943–950.
Habak, C., Wilkinson, F., & Wilson, H. R. (2009). Preservation of shape discrimination in aging. *Journal of Vision, 9*, 1–8.
Hadad, B., & Kimchi, R. (2008). Time course of grouping of shape by perceptual closure: Effects of spatial proximity and collinearity. *Perception & Psychophysics, 70*, 818–827.
Hadad, B., Maurer, D., & Lewis, T. L. (2010). The effects of spatial proximity and collinearity on contour integration in adults and children. *Vision Research, 50*, 772–778.
Hess, R. F., & Dakin, S. C. (1999). Contour integration in the peripheral field. *Vision Research, 39*, 947–959.
Hess, R. F., Hayes, A., & Field, D. J. (2003). Contour integration and cortical processing. *Journal of Physiology—Paris, 97*, 105–119.

Kovács, I. (2000). Human development of perceptual organization. *Vision Research, 40*, 1301–1310.
Kovács, I., Kozma, P., Fehér, Á., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proceedings of the National Academy of Sciences, 96*, 12204–12209.
Ledgeway, T., Hess, R. F., & Geisler, W. S. (2005). Grouping local orientation and direction signals to extract spatial contours: Empirical tests of "association field" models of contour integration. *Vision Research, 44*, 2511–2522.
Leventhal, A. G., Wang, Y. C., Pu, M. L., Zhou, Y. F., & Ma, Y. Y. (2003). GABA and its agonists improved visual cortical function in senescent monkeys. *Science, 300*, 812–815.
Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America, 49*(Suppl. 2), 467.
McIntosh, A. R., Sekuler, A. B., Penpeci, C., Rajah, M. N., Grady, C. L., Sekuler, R., et al. (1999). Recruitment of unique neural systems to support visual memory in normal aging. *Current Biology, 9*, 1275–1278.
McKendrick, A. M., Weymouth, A. E., & Battista, J. (2010). The effect of normal aging on closed contour shape discrimination. *Journal of Vision, 10*, 1–9.
Norman, J. F., Crabtree, C. E., Norman, H. F., Moncrief, B. K., Herrmann, M., & Kapley, N. (2006). Aging and the visual, haptic, and cross-modal perception of natural object shape. *Perception, 35*, 1383–1395.
Owsley, C. (2011). Aging and vision. *Vision Research, 51*, 1610–1622.
Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.
Roudaia, E., Bennett, P. J., & Sekuler, A. B. (2008). The effect of aging on contour integration. *Vision Research, 48*, 2767–2774.
Roudaia, E., Farber, L. E., Bennett, P. J., & Sekuler, A. B. (2011). The effects of aging on contour discrimination in clutter. *Vision Research, 51*, 1022–1032.
Sara, M., & Faubert, J. (2000). Aging, perception, and visual short-term memory for luminance-defined form. *Ophthalmic & Physiological Optics, 20*, 314–322.
Schmolesky, M. T., Wang, Y., Pu, M., & Leventhal, A. G. (2000). Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience, 3*, 384–390.
Wang, Y. Z. (2001). Effects of aging on shape discrimination. *Optometry and Vision Science, 78*, 447–454.
Wright, L. A., & Wormald, R. P. (1992). Stereopsis and ageing. *Eye, 6*(Pt 5), 473–476.